

Investigation of Freeze and Thaw Cycles of a Gas-Charged Heat Pipe

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The traditional constant conductance heat pipes (CCHPs) currently used on most spacecraft run the risk of bursting the pipe when the working fluid is frozen and later thawed. One method to avoid pipe bursting is to use a gas-charged heat pipe (GCHP) that can sustain repeated freeze/thaw cycles. The construction of the GCHP is similar to that of the traditional CCHP except that a small amount of non-condensable gas (NCG) is introduced and a small length is added to the CCHP condenser to serve as the NCG reservoir. During the normal operation, the NCG is mostly confined to the reservoir, and the GCHP functions as a passive variable conductance heat pipe (VCHP). When the liquid begins to freeze in the condenser section, the NCG will expand to fill the central core of the heat pipe, and ice will be formed only in the grooves located on the inner surface of the heat pipe in a controlled fashion. The ice will not bridge the diameter of the heat pipe, thus avoiding the risk of pipe bursting during freeze/thaw cycles. A GCHP using ammonia as the working fluid was fabricated and then tested inside a thermal vacuum chamber. The GCHP demonstrated a heat transport capability of more than 200W at 298K as designed. Twenty-seven freeze/thaw cycles were conducted under various conditions where the evaporator temperature ranged from 163K to 253K and the condenser/reservoir temperatures ranged from 123K to 173K. In all tests, the GCHP restarted without any problem with heat loads between 10W and 100W. No performance degradation was noticed after 27 freeze/thaw cycles. The ability of the GCHP to sustain repeated freeze/thaw cycles was thus successfully demonstrated.

I. Introduction

Traditional constant conductance heat pipes (CCHPs) have been widely used for spacecraft thermal control. The operating principles of a CCHP can be found in several sources¹⁻³. One potential issue with the CCHP is the formation of a solid ice plug that bridges the diameter of the pipe at the condenser end when the spacecraft radiator is exposed to a thermal environment colder than the freezing point of the working fluid, as shown in Figure 1. Until the ice plug is melted and the heat pipe resumes its heat transport function, the instrument cannot be safely turned on. Meanwhile, the pipe runs the risk of bursting when the ice is formed or melted, depending on the thermal properties of the working fluid. The current practice is to avoid the CCHP freezing by heating the radiator above the freezing point of the working fluid during the spacecraft survival mode. The required control heater power can be very large and may become prohibitive for power constrained satellites.

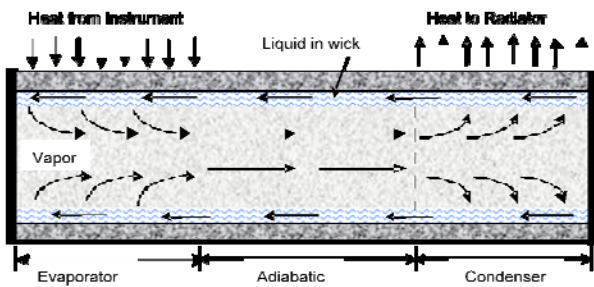
The Lunar thermal environment typically includes long periods in extremely cold thermal environments^{4,5}. The aforementioned risk of CCHP bursting is a real issue for such applications. One method to avoid heat pipe bursting is to use a gas-charged heat pipe (GCHP) that can sustain repeated freeze/thaw cycles. The construction of a GCHP is similar to the traditional CCHP except that a small amount of non-condensable gas (NCG) is introduced and a small length is added to the CCHP condenser to serve as the NCG reservoir. During the normal operation, the NCG is mostly confined to the reservoir, and the GCHP functions as a variable conductance heat pipe (VCHP). When the liquid begins to freeze in the condenser section, the NCG will expand to fill the central core of the heat

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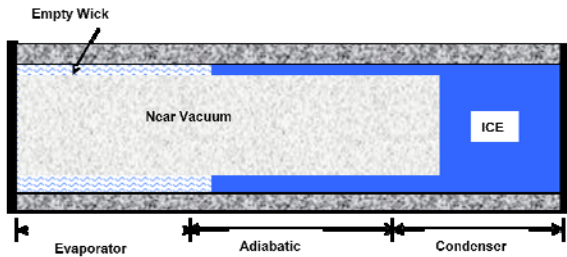
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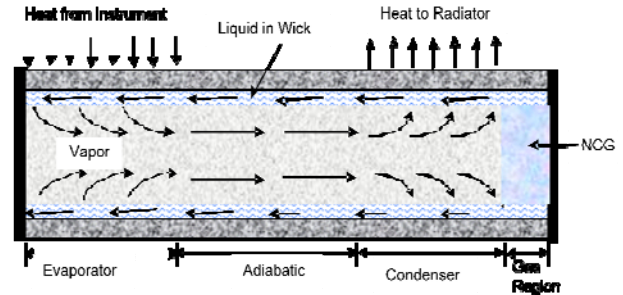
pipe. Ice will be formed only in the grooves located on the inner surface of the heat pipe in a controlled fashion as shown in Figure 2. When the radiator is coming out of the shade, the instrument can be turned on. The ice near the evaporator section will be melted first, and the liquid will be vaporized. The vapor will move toward the condenser section. The heat carried by the vapor plus the heat conducted through the metal shell will melt the adjacent ice. The ice in the condenser section may also be melted by the sun light. The process will continue until all the ice is melted and the heat pipe resumes its full heat transport capability. Because no solid ice plug is formed to bridge the heat pipe diameter, there is no danger of pipe bursting during the freezing or melting process. In addition, the entire operation of the GCHP is passive and self-regulating.



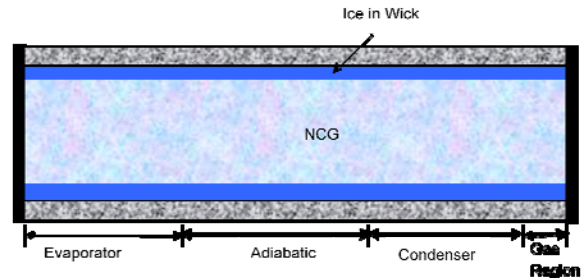
(a) Normal Operation of a CCHP



(b) Formation of an Ice Plug in a CCHP



(a) Normal Operation of a GCHP



(b) Formation of Ice in a GCHP

Figure 1. CCHP Operation

Figure 2. GCHP Operation

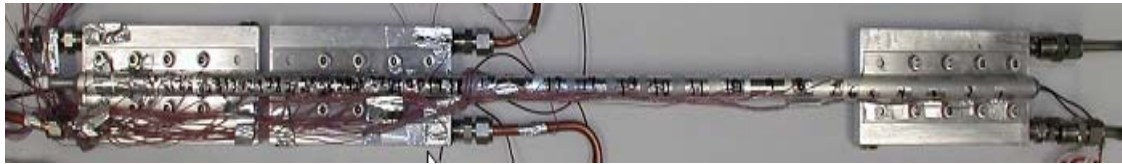
The feasibility of a GCHP to start from a frozen state has been demonstrated with the GCHP maintained below the freezing temperature of its working fluid for a long period of time (up to 15 days). However, only very limited tests were conducted⁵. This paper describes the test of a GCHP designed to sustain repeated freeze/thaw cycles typically encountered in spacecraft applications. For comparison, a traditional CCHP of the same design but without the NCG and the NCG reservoir is also fabricated and tested. The following sections present the design and fabrication of the two heat pipes, and their performance tests under a thermal vacuum environment.

II. Test Article and Test Setup

The GCHP test article is made of aluminum 6063 T6 with an outer diameter of 12.83 mm and a vapor core diameter of 7.87 mm. The vapor grooves are of the trapezoidal shape. Lengths for the evaporator, adiabatic section, condenser and NCG reservoir are 127 mm, 305 mm, 127 mm, and 140 mm, respectively. The working fluid is 99.998% purity anhydrous ammonia. The pipe is charged with 8.97 grams of ammonia, and 58 mg (2.88×10^{-3} gram-mole) of neon as the NCG. Design requirements of the GCHP include: 1) The pipe shall be able to transport at least 200W of heat at 298K; 2) The condenser shall be > 90% open for vapor condensation when the vapor is at 298K and the condenser sink is at 243K; and 3) The amount of NCG shall be sufficient to close the condenser plus at least 102 mm of the adiabatic section when the condenser sink temperature is ≥ 153 K and the vapor temperature is ≤ 253 K. A CCHP with the same dimensions but without the NCG and NCG reservoir is also fabricated. Figure 3 shows pictures of the CCHP and the GCHP used in this test program.



(a) CCHP



(b) GCHP

Figure 3. Pictures of the CCHP and GCHP

The CCHP and GCHP were placed inside a thermal vacuum chamber for performance tests. The CCHP was tested first, followed by the GCHP. Figure 4 shows the thermal vacuum chamber used for the tests. Nitrogen gas was employed to cool the condenser of the heat pipes and the reservoir of the GCHP during the performance tests. In addition, nitrogen gas was also used to pre-condition the evaporator, condenser, and the reservoir prior to each test. Figure 5 shows the heat pipe placed inside the chamber. The entire heat pipe was covered with multi-layer insulation. Cartridge heaters were attached to the evaporator flange to provide the heat load. Also shown in Figure 5 are the copper tubes for the nitrogen coolant flows. Thermocouples were used to monitor the temperatures. Figures 6 and 7 show the thermocouple locations for the CCHP and GCHP tests, respectively. A sufficient number of thermocouples were installed in the condenser section to monitor the vapor and liquid interface along the pipes. A data acquisition system consisting of a data logger, a personal computer, and a screen monitor was used to collect, display, and store temperature and power data every second. LabView software was used for the command and control of the test conditions.



Figure 4. Thermal Vacuum Chamber for CCHP and GCHP Tests

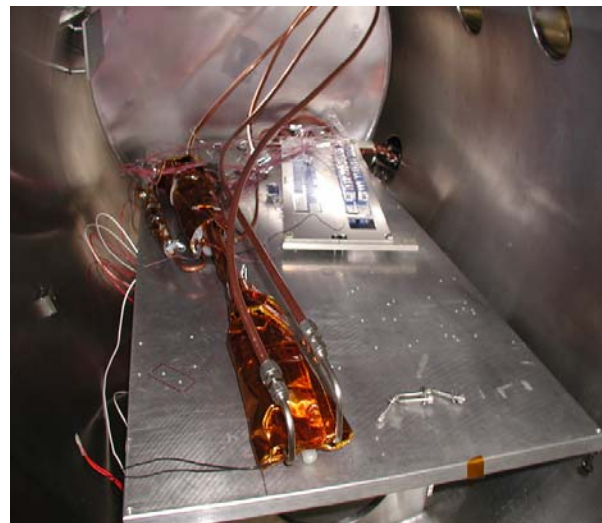


Figure 5. Heat Pipe inside the Thermal Vacuum Chamber

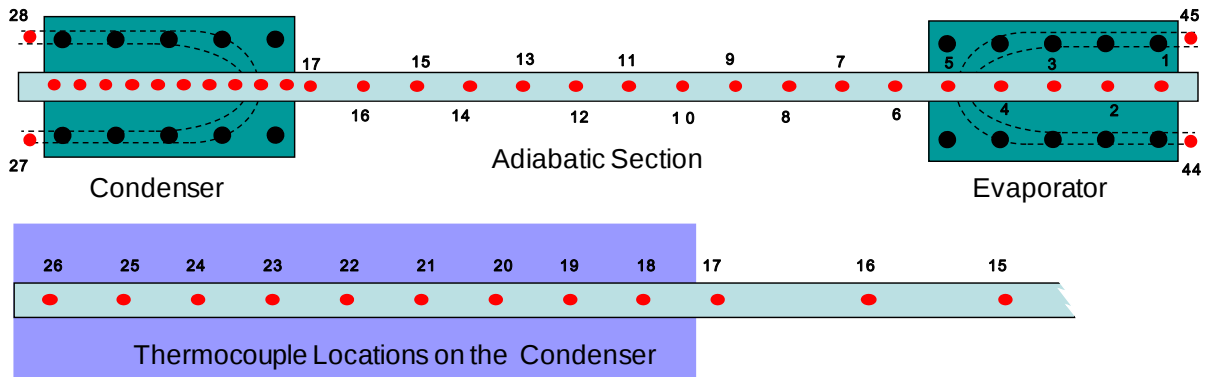


Figure 6. Thermocouple Locations for CCHP Test

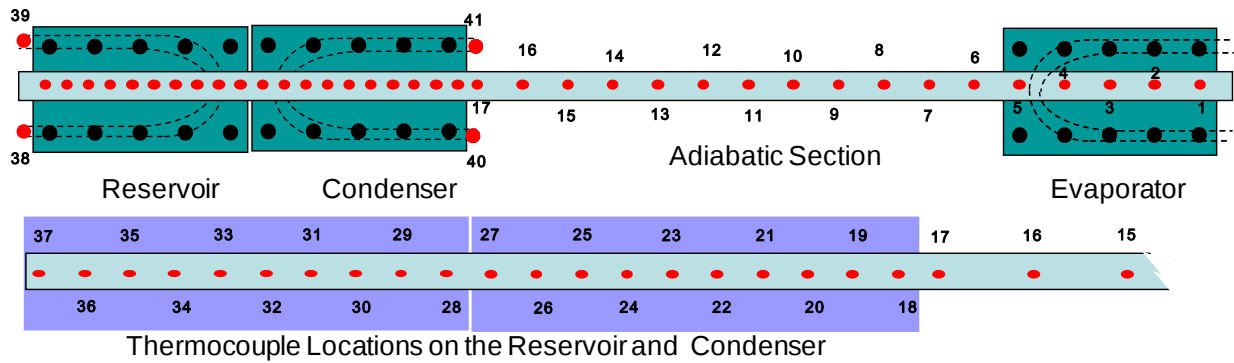


Figure 7. Thermocouple Locations for GCHP Test

III. Test Results

Heat transport tests were conducted first for the CCHP and GCHP at condenser sink temperatures of 253K, 263K, 273K, 283K, and 293K, respectively. Each heat pipe demonstrated a heat transport capability of more than the required 200W under these conditions. Figures 8 and 9 illustrate typical thermal behaviors during the heat transport test. Based on these test results, the overall thermal conductance from the evaporator to the condenser sink was calculated by dividing the heat load by the temperature difference between the evaporator and the condenser sink. Figure 10 shows the CCHP had an overall thermal conductance of about 4.5W/K, while Figure 11 shows that the GCHP exhibited the behavior of a VCHP as expected with the thermal conductance varying between 0.8 W/K and 5.0 W/K, depending on the test conditions.

The GCHP was then subjected to freeze/thaw cycles. Twenty-seven freeze/thaw cycles were tested under various conditions where the evaporator temperature ranged from 163K to 253K and the condenser/reservoir sink temperature ranged from 123K to 173K. The freezing period was kept between 2 to 6 hours before power was applied to the evaporator to restart the GCHP. In some tests, the evaporator temperature was kept above the freezing point of ammonia (196K) while the condenser section was frozen. In other tests, the entire heat pipe including the evaporator was allowed to freeze. The power applied to the evaporator to restart the GCHP ranged from 10W to 100W. In all tests, the GCHP restarted without any problem. The ability of the GCHP to sustain freeze/thaw cycles was therefore successfully demonstrated.

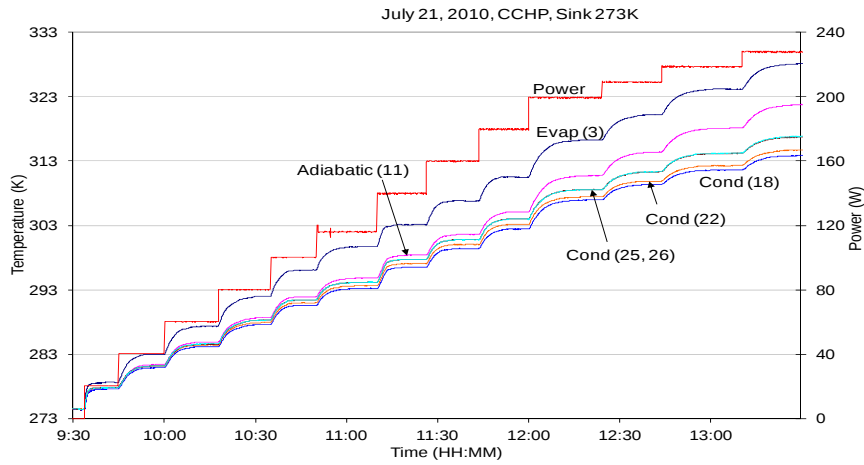


Figure 8. CCHP Heat Transport Test at 273K Sink Temperature

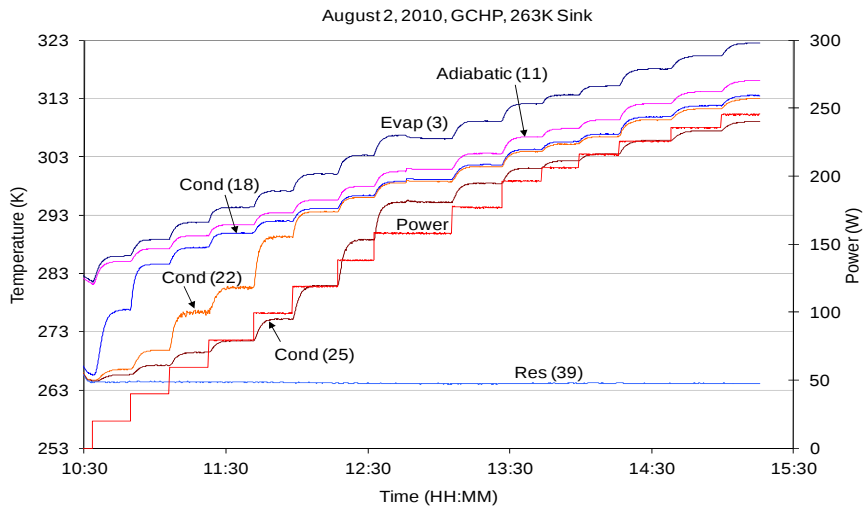


Figure 9 GCHP Heat Transport Test at 263K Sink Temperature

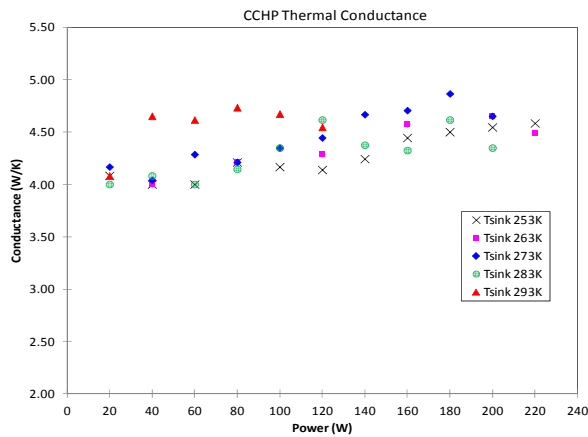


Figure 10. Overall Thermal Conductance of the CCHP

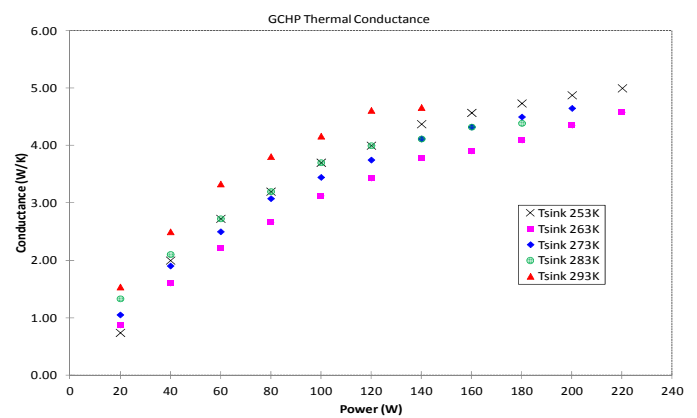


Figure 11. Overall Thermal Conductance of the GCHP

Figure 12 shows the temperature profiles of the GCHP in a typical freeze/thaw cycle test where the evaporator temperature was kept at 233K, which was above the freezing point of ammonia (196K). This test simulated the condition where the instrument was kept at the 233K minimum allowable temperature while allowing the condenser to freeze. The GCHP was able to restart with a frozen condenser by applying 20W to the evaporator.

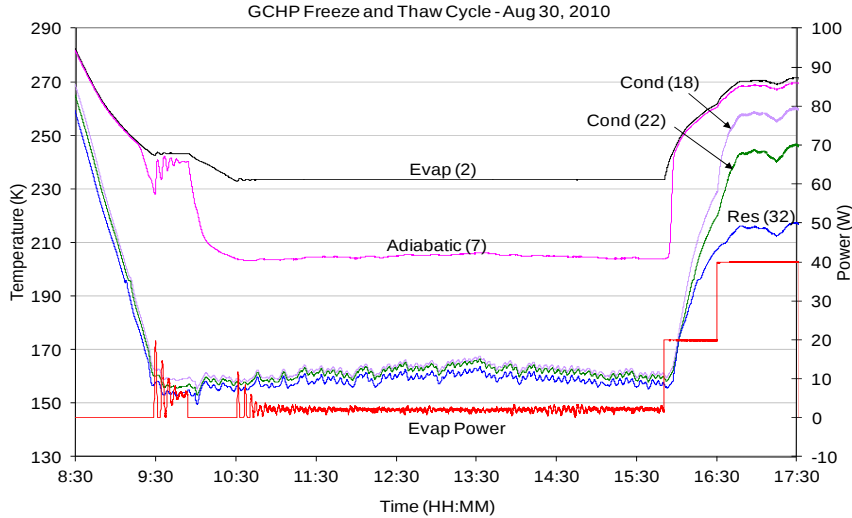


Figure 12. Temperature Profiles in a Typical GCHP Freeze/Thaw Cycle Test

Figure 13 and 14 illustrate details of the temperature profiles during the freezing and thawing of the GCHP, respectively. Note the flatness of the condenser temperatures around the ammonia freezing point of 196K in both figures. The condenser temperatures in Figure 13 indicated that the condenser froze progressively from the reservoir end toward the evaporator end as the vapor temperature/pressure dropped and the NCG expanded. Similarly, in Figure 14 the ice thawed progressively from the adiabatic section toward the reservoir during the restart. As the vapor temperature/pressure increased, the NCG contracted and the vapor was pushed into the reservoir.

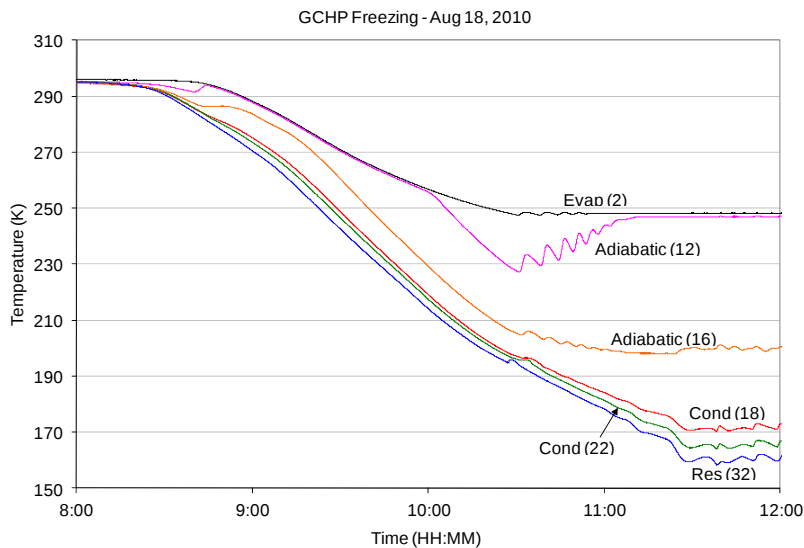


Figure 13. Temperature Profiles for Freezing of the GCHP

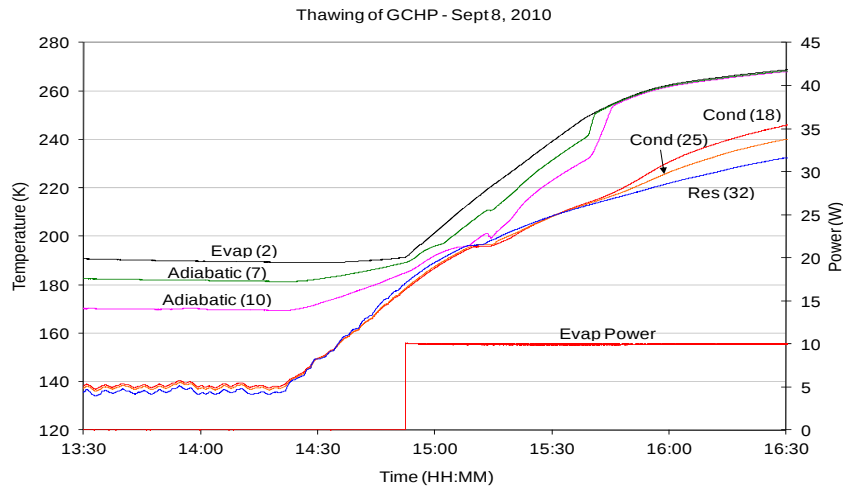


Figure 14. Temperature Profile for Thawing of the GCHP

The GCHP not only allows the condenser to freeze in a controlled fashion so that no ice plug bridging the diameter of the pipe will be formed, but also allows the condenser to thaw in a similar manner during the restart. This is not the case for a CCHP. For a frozen CCHP, the entire condenser is open for the vapor condensation during restart. If the applied power is not sufficiently large to overcome the energy loss through the condenser, the evaporator will eventually dry out, and the restart will fail⁶⁻⁸. With a GCHP, at startup from frozen conditions, the NCG occupies a majority of the condenser section, significantly reducing the cooling rate of the condenser. Thus, the GCHP restarts by thawing a small section of the condenser and increasing this section length as more vapor pressure becomes available to contract the NCG. This process continues until the active length of the condenser is appropriate for the power level.

Figure 12 shows that the GCHP could restart from a frozen condenser by applying 20W to the evaporator followed by 40W, while Figure 14 shows that the GCHP restarted with 10W to the evaporator. For comparison, Figure 15 shows the temperature profiles of a successful restart of the GCHP with 100W to the evaporator.

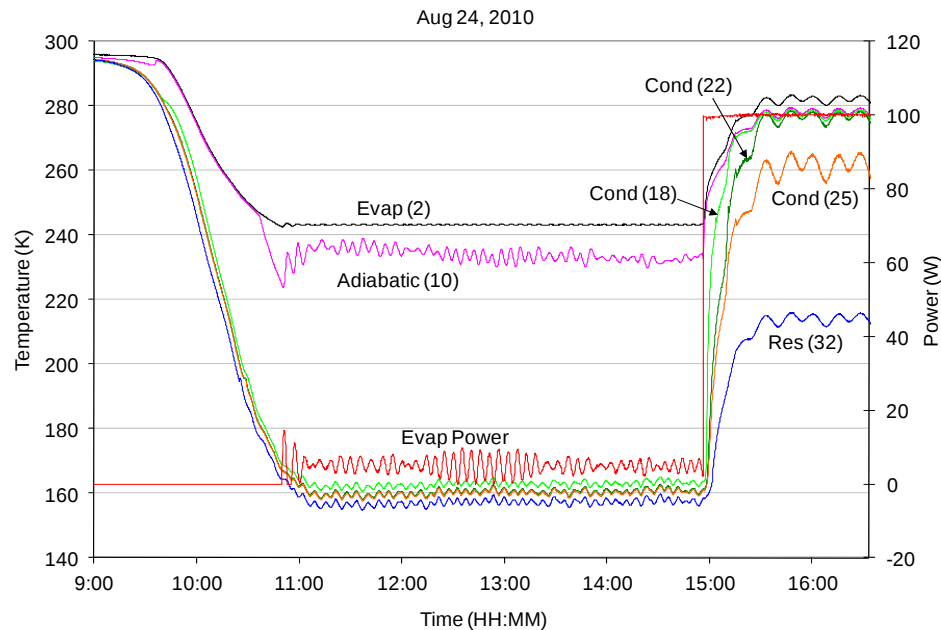


Figure 15. Temperature Profiles for restart of the GCHP with 100W

In the above tests, the evaporator was maintained above the freezing point by applying a small amount of heat to the evaporator. In practical applications, this is achieved by using a survival heater attached to the instrument. If such a survival heater is not available, the evaporator will eventually freeze after the heat pipe is exposed to a cold environment for a prolonged period. Figure 16 illustrates the temperature profiles of the GCHP when the entire GCHP was allowed to freeze, and then restarted by applying 50W to the evaporator. Figure 17 depicts the temperature profiles of the GCHP for another similar test except the pipe restarted with 10W to the evaporator. In both cases, the restart was successful.

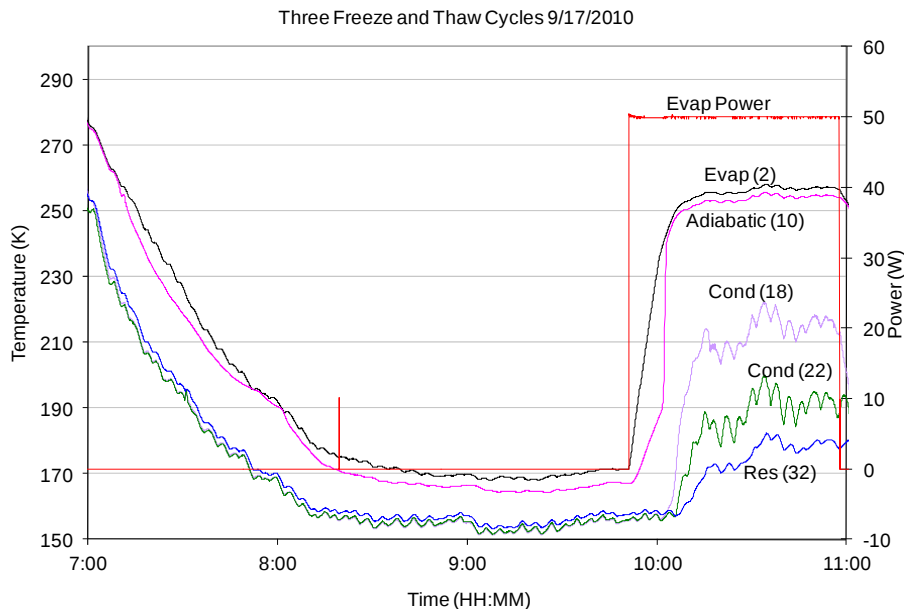


Figure 16. Temperature Profiles for Freezing the Entire GCHP and Restarting with 50W

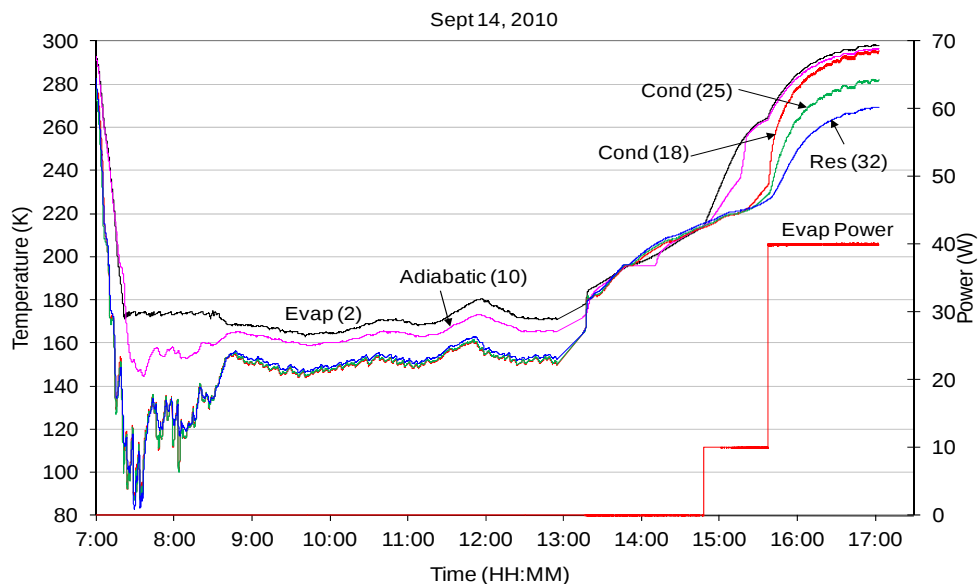


Figure 17. Temperature Profiles for Freezing the Entire GCHP and Restarting with 10W

Figure 18 depicts the temperature profiles when the GCHP was subjected to repeated freeze/thaw cycles. During the freezing cycle, the entire GCHP was frozen for about 60 minutes, and then the GCHP restarted with 50W to the evaporator. Figure 19 shows the temperature profiles for a similar test where the entire GCHP was frozen and the pipe restarted with 100W to the evaporator.

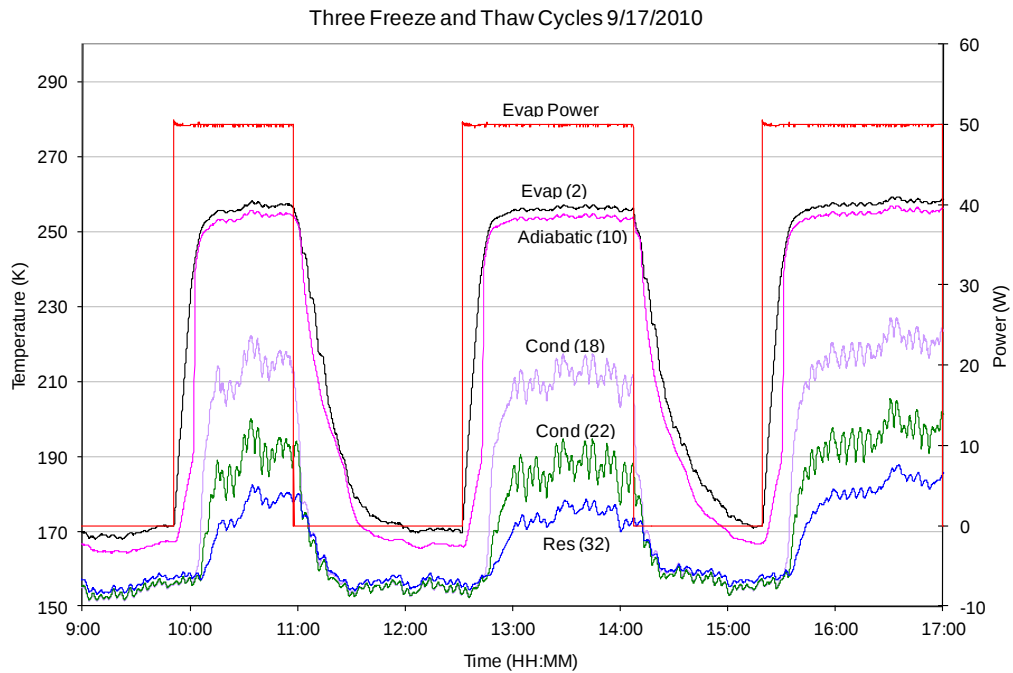


Figure 18. Freeze and Thaw Cycles of GCHP with 50W for Restart

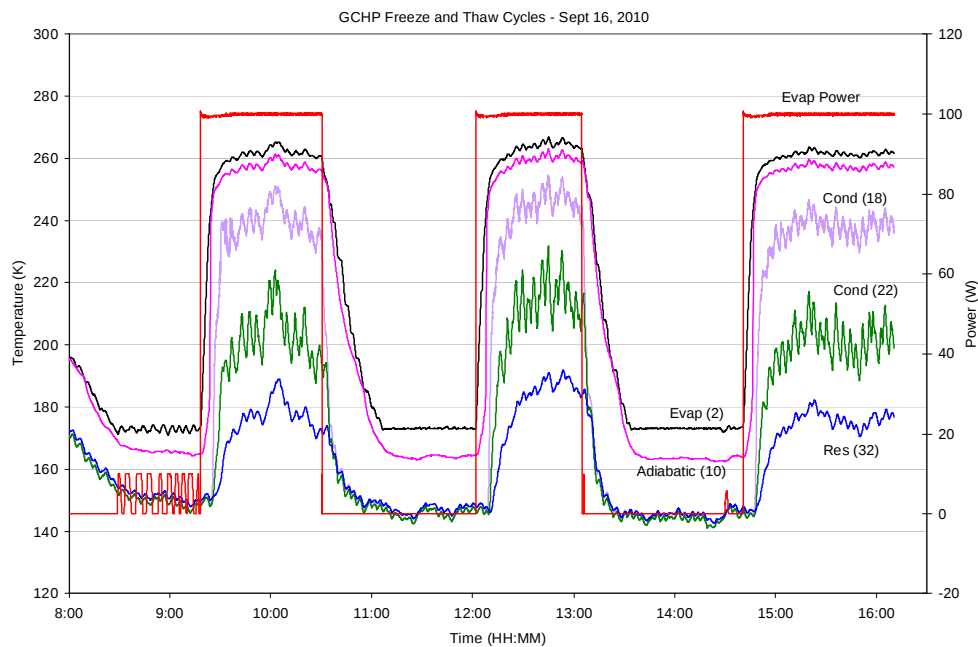


Figure 19. Freeze and Thaw Cycles of GCHP with 100W for Restart

After twenty-seven freeze/thaw cycle tests were completed, the GCHP was tested again for its heat transport capability. No performance degradation was noticed when compared to the tests conducted prior to the freeze/thaw cycles. Figure 20 shows the GCHP temperature profiles for the heat transport test at a condenser sink temperature of 263K.

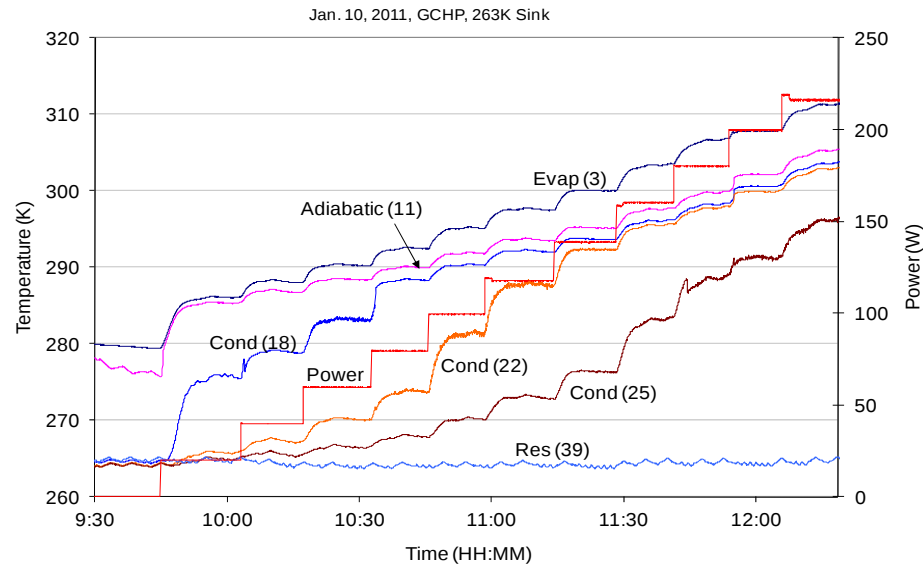


Figure 20 GCHP Heat Transport Test at 263K Sink Temperature after 27 Freeze/Thaw Cycles

VII. Conclusion

This investigation verifies that a simple GCHP constructed by adding an additional length to the traditional CCHP and charging it with a pre-determined amount of NCG can sustain repeated freeze/thaw cycles without bursting the pipe. The GCHP has the same heat transport capability as the CCHP of the similar design and works as a passive VCHP. After subjected to 27 repeated freeze/thaw cycles, the GCHP showed no degradation in its heat transport capability. The GCHP can save substantial power for the spacecraft, add more versatility and higher reliability to the thermal subsystem, and simplify the spacecraft thermal, mechanical, and electrical subsystem designs. Furthermore, the technology is applicable to various working fluids over a wide range of temperatures, and will have very broad applications.

Acknowledgments

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